Subject Index

A

Acoustic waves, 536-546 diffracted and mode converted signals, 541-542 distributed spring constant, 539-541 interaction with crack, 536-537 interface transmissivity, 539, 541 local stress intensity factor, 543-546 receiving through transmission and diffracted signals, 537-538 residual stress across interface, 542-543 shear wave signals, 542 ultrasonic transmission past crack, 539-540 wave propagation perpendicular to crack surface, 538-541 Airy stress function, 313 Alloys, 139, 171 Aluminum alloy, 121, 270, 528, 583-597, 640, 642-643 applied versus effective specimen geometry, 227-228 baseline propagation data, 571-572 chemical composition, 122, 584 compliance method, 587 constant load amplitude tests, 569-570 crack growth baseline data, 428-430 rate variation, 37-38 crack opening stress intensity factor variation, 37-38

effective stress intensity range ratio. 124-125 fatigue loading variables rates, 142--143 mechanical properties, 123, 217, 584 overloads, 592-595 procedure, 584-585 properties, 529 specimen geometry, 584 stress intensities, 225, 228 stress ratio effect, 588-590 stress state effects, 590-592 tensile properties, 570 transmission coefficient, 539 Aluminum allow 2024-T3, 505-515 crack opening load, determination, 508-509 experimental procedure, 506-509 load-shedding procedures, 507-508 6% load-step tests, 509-513 18 and 30% load-step tests, 513-514 Aluminum alloy 2124, 300-316 chemical composition, 302 closure load, 308 crack growth rate, variation, 308-310 crack path morphology, 305, 309 crack propagation of long cracks, 304, 307-308 experimental procedures, 306 finite-element predictions, 305, 309 grain structure, 302, 306 long crack threshold data, 304, 308, 311

Aluminum alloy—Continued mechanical properties, 303 numerical analysis, 306, 308 plastic zone shapes, 312, 314 stress intensity factor, variation, 311, 314 Analytical crack opening model, basic equations, 456 Asperities, 459-474 crack tip between initial notch tip, 467-468, 470 near, 468-471 density, 542 geometric, 112, 116 initial notch tip, 468-470 model, 461 Asperity contact, 179, 181, 536-538 along fracture surfaces, 542 residual stress field, 537-538 ultrasonic techniques, 537 ultrasound interaction, 538-542 Asperity-induced crack closure, 164 Asperity strip, local stress intensity factor, 544 ASTM E 399, 113, 321, 324, 340, 570, 574, 577 ASTM E 647, 175–176, 219, 227, 233, 253, 505-507, 515, 529

B

Backface strain, 96, 98, 172, 183, 186, 197, 247, 306, 639 far-field closure, 193–195 load-displacement date, 175–176 PMMA, 206–207 Bending fatigue, 260 Binary Fe-Si alloys chemical composition, 114 compact-tension specimen, 113 fatigue crack propagation, 114, 116 grain size, 115 yield strength, 115 Block loading history, 282, 291–292 Bodner coefficients, Ti-6246, 363
Bodner-Partom constitutive relations, 363
BS 4360-50D, 261-262, 267-268
Budiansky and Hutchinson model, 59, 638

С

Calibration factor, 272 Carbon steel, 475, 480 Center-cracked panel, 319 closure transient, 332, 335 crack profile, 332, 335 loading, 321 overloads and underloads, 446-448 plastic zone size, 324, 326 Chevron region, 36 Clip gage, 262 compliance measurements, 17 Elber type, 262, 530, 640 locations for closure detection, 263 position, 587–588 Closure force numerical definition, 384 variation versus mesh length, 387-388 Closure load, 270 aluminum alloy 2124, 308 defined, 273 versus stress intensity factor, 372-373 Closure parameter, 612 defined, 265 variation with statistical approach, 265-266 Closure transient, center-cracked panel, 332, 335 CMOD, 183, 187, 639 far-field closure, 193-195 gage, 219 versus load, 154-155, 374-377 load-displacement date, 175-176

measurements, 197 PMMA, 206-207 CMOD method, 172 Cochran's test for equality of variance, 244 COD, 44, 270, 321, 598 closure/opening load definitions, 605-607 crack-tip strain and, 52, 54 dynamic, 541 versus load, 375-377 procedures, measurement 272 - 274partially and fully open cracks, 48 - 50pattern crack face as function of size, 607 Type II crack, 603–604 various distances from crack tip, 606 profiles applied load, 605 PMMA, 602-605 zero load, 602-603 statistical approach, 274 Compliance, 98–99 versus crack length, 275-276 fully open crack, 607 measurements, 17-18 before and after overload, 531, 533 crack length, 154 with more than one linear part, 21 method aluminum alloys, 587 global, 639 statistical approach, 274-275 Compliance-crack length equation, 207Compressive loading, 62, 89 crack growth threshold behavior, 82-84 Constant amplitude cycling, 98–102 Constant-amplitude loading, 24, 30

aluminum alloys, 569-570 closure and opening profiles, 404 crack growth, 454 threshold, 383 crack opening load, 447-448 elastic and plastic singularities, 389 finite-element analysis, 403-409 single-spike overload, 409-411 strip yield model, 444-445 Constant- K_{max} tests, 511–513 Constitutive model, 343-344 Copper crack closure, 69-70 fracture surfaces, 66, 68 near-threshold fatigue crack growth rates, 65 CORPUS model, 438, 449-450, 641 comparison with strip yield model, 450-452 crack opening behavior, 449 landing gear loading, 452-455 Crack peeling open, 127-128 plastic castings, 14 unzipping behavior, 216 Crack arrest, 558-559, 562 Crack closing load absolute values, 610-611 divided by maximum applied load, 611 as function of crack length, 369-370 mean versus percent offset, 223 Crack closure, 5-6, 35, 139-148 analytical developments, 25-27, 641-642 applications, 642-644 averaging, 226 comparison of local and remote measurements, 125-128 concept, 132, 549 validity, 471 copper, 69-70 correlation based on, 524-526 cryogenic temperatures, 77

Crack closure—Continued dependence on fatigue loading variables, 124-126 direct observation, 16-17 Elber's concept, 132 Elber's definition, 586–587 Elber's model, 140 experimental procedure, 141-142, 227-229 extent of, 560-563 far-field, 87, 102 versus near-tip closure, 104 - 108fracture surface contacts, 14 as function of crack wake length, 569 importance, 230 indirect observations based on fatigue crack growth, 18-20 intrinsic and extrinsic factors, 44 level determinations, 223 growth rates and, 144-145 load-cancelled displacement traces, 142-143 macrocracks, 10-11 microcracks, 9-10 Mode I and II, 57-58 near-threshold, 62-92, 224, 227, 311, 638 grain size, 70-71 microstructure effects, 65-74 yield strength, 65-70 nomenclature, 301 numerical aspects of relations, 21 - 25progress, 520-521 sources, 150 at start of test, 224, 226 stress, 403 as function of applied stress, 354 structurally sensitive macrocrack growth, 14-16 surface, 595 technical approach, 222-227

technical significance, 7-8 test method, 519 three-dimensional nature, 134 thresholds, 93, 300 two-dimensional model, 25 under tensile load, 20 variable amplitude loading, 101 - 103wake-induced, 59 Crack closure ligament model, 414-436 comparison with Glinka's crack growth data, 423-425 Liu's crack growth data, 425-429 crack closure approach, 416-417 elastic and elastic-plastic stress distributions, 418-419 elastic stress fields, comparison with LEFM, 419 element schematic, 415-416 element width influence, 417-418 growth life, 427 Keyvanfar and Nelson's data, 429-431 modified Paris law, 418 outline, 415-416 residual stress field, in front of and in wake of crack, 420-422 redistribution, 419-421 specimen partitioning, 415 stress distribution change caused by element cut, 419-420 variation of opening stress with element width, 417 Crack closure model, 491-504 applications, 497–503 to surface crack propagation, 594-595 based on Forman's equation, 523-525 crack closure, 520-522 crack closure tests, 519, 521 crack growth

at Cycle i, 494 law, 492 stress ratio, 516-527 crack propagation tests, 518-519 data correlation, 522-525 determination of parameters, 496-499, 501 examples, 497-499 history values, 493-494 material, 517-518 opening point selection, 492-493 rain-flow effect, 493-495 specimen design and manufacture, 518 tensile portion of stress cycle, 522, 524 truncation level, 502 see also Models Crack closure points, as function of crack length, 484-486 Crack extension, constant-amplitude, 403 Crack face, COD pattern as function of size, 607 Crack-filling closure, 35 Crack front overload, 533 plane strain/plane stress, 11-12 reproduction, 594-595 Crack growth, 171, 186, 197, 230, 260, 459 accelerations, 25 characteristics, 614-615 constant amplitude, 285–291, 454 correlation of J integral, 286, 288residual stress effects, 425-429 crack closure ligament model, 416-418 crack opening, 354, 357 crack opening load, 445 cyclic, analytical model, 362 decreasing load threshold testing, 554-555 delays, 642 discretization, 443

elastic-plastic parameters, 288 experimental and predicted, 294-295 extremely slow growth rate, 15 finite-element analysis, 402 as function of stress intensity factor, 560–561 decreasing load threshold tests, 557 history, 365 indirect closure observations, 18 - 20intergranular, 563 law, 441, 492 life predictions, 427, 491 mechanisms, 548 models, 437, 441-443 near-threshold, 557-559, 642-643 perturbation acceleration, 595 prediction, 27-29, 381, 455 fractography to check, 28-29 resistance, 5 retardation, 25 during constant amplitude loading, 257 overloads, 20-21 simplified landing gear load sequence, 452-455 simulation, 328, 330 small-scale yielding, 319-320 50D steel, 267-268 three-dimensional nature, 303 threshold, 380-397 constant amplitude loadings, 383 elasto-plastic stress-strain, 392 experimental setup, 382 no-growth threshold force, 393, 396 numerical simulation, 381-383 opening force, mesh independent determination, 390 plastic strain tensor variation, 390-393 propagation simulation, 384 transient, 638

Crack growth—Continued under VA-loading, 25 Crack growth rate against stress intensity factor, 507, 509-513 applied load, 612, 614 and closure levels, 144-145 at depth point, 589 differences in air and vacuum, 563 versus frequency, 114, 116 as function of effective stress intensity factor, 391, 393, 589, 629-630 long cracks, 302-303 maximum CTOD, 469 minimum, following overload, 533 3-Ni steel, 242 predictions, 430 progressive reduction, 309-310 regimes, 23 retardation, overloads, 596 small cracks, 302-303, 625-633 stress intensity factor, 24 decreasing procedure, 144, 146 stress ratio and, 40-41 stress state effects, 591 surface cracks, 590 surface flaw large and small specimens, 626, 628-629 large cracks, 625-627 small cracks, 625-627 titanium-aluminum alloys, 156-157 variation aluminum alloy 2124, 308-310 with stress intensity range or crack length, 301-302 Crack initiation, near specimen center, 534 Crack length average, 199-200 closure as function of large cracks, 622-624

load, as function of large cracks, 622-623 versus compliance, 275-276 compliance measurements, 154 crack opening as function of, 348-349 versus cycles, decreasing load threshold testing, 554-555 effective stress range ratio as function of, 293 versus elapsed cycles response, 200fully closed, 560-561 fully open, extent of closure as function of, 561, 563 as function of applied load, 202-203, 206-207 as function of normalized closure, 305, 309 versus near tip closure, 192-193 opening and closing loads as function of, 369-370 opening and closing points as function of, 484-486 versus opening load ratio, 275-277 opening stress intensity effect, 175, 177-178 stress intensity factor as function of, 552 threshold values, 306 Crack mouth opening displacement, see CMOD Crack opening versus applied load, 46-47 behavior during block history, 291-292 constant amplitude cycle, 283 crack growth, 354, 357 displacements, 48-51 Elber's definition, 588 as function of crack length, 348-349 ideal two-dimensional, 11 load magnitude, 47-48 model, 437

modelled in CORPUS, 449 plane strain, 330-337 plane stress, 357-358 plasticity induced crack closure, 462 point opening, as function of crack length, 484, 486 selection, 492-493 profile, 203--204, 599 stationary crack, 324-325 stress intensity, 112 surface and interior distinction, 587 tearing crack response, 327 variable amplitude loading, 448-452 wake effects, 446 Crack opening load, 44, 208-209, 230, 437, 640 constant amplitude loading, 447-448 crack growth, 445 crack length and, 207 versus crack opening displacement behavior, 233-234 determination, 508-509 Dunnett's critical D statistic, 245 as function of crack length, 369-370 growth rates, 241 from load displacement data, 214-221 experimental methods, 219 materials, 218 normalized, versus interval size, 234-235 overload level effect, 447 prediction, 443-444 ratio, 322 versus crack length, 275–277 statistical approach, 274-275 stabilized, 445 determination, statistical 233-234, 242-246 stress ratio, 508, 510-511

strip yield model, 441 underload level effect, 447 variation during flight block, 454-455 see also Titanium-aluminum allovs Crack opening stress, 398, 404 as function of applied stress, 354 as function of stress level, 284, 295-296 intensity as function of test frequency, 115, 118 polycrystalline specimens, 115, 119 single crystal specimens, 115, 117 interior and exterior planes, 408-409 levels, 7, 345, 641 during ΔK -decreasing tests, 15 measurement methods, 16 stationary VA test, 27 from striation measurements, 19 normalized, 404-405 prediction of changes, 431 stress ratio effects, 421-423 variation with element width, 417 Crack path morphology, 101, 305, 309 profile, 99, 104 Crack profile, center-cracked panel, 332, 335 Crack propagation, 35, 62, 149, 214, 279, 319, 414, 437, 505, 568, 617 analysis, 139–140 behavior, 250 binary Fe-Si alloys, 114, 116 constant amplitude load, 384 during variable amplitude histories, 297 forced, 385-386 Forman's equation, 523-525 HiLo tests, 392-396

Crack propagation—Continued long cracks, 304, 307-308 simulation, 384 surface, crack closure model application, 594–595 tensile range of stress intensity factor, 522, 524 test method, 518 total stress intensity factor range, 522-523 Crack propagation rate acceleration after transition, 580 constant amplitude, 98-99 effective opening and closing stress intensity factors, 482-483, 485 fractographs used to measure, 577-579 as function of effective stress intensity factor, 524-526, 575 function of stress intensity range, 568-569 maximum stress intensity factor, 482, 484 measured from striation spacings, 576-577 near-threshold, see René 95 S-shaped unloading curve method, 482-486 stress ratio effect, 517 Crack shape factor, 595 Crack size, 62, 89 near-threshold growth, 84-86 small- and large-crack data convergence, 163 see also Large cracks; Small cracks Crack surface contact profiles, 404 displacements, 456-457 exterior plane, 407, 409 interior plane, 406, 409–411 elastic-plastic elements, 461 intersection points, 265 Crack tip, 607 α/β -processed Ti-6242S, 174-175

asperities between initial notch tip, 467-468, 470 near, 468-471 closure stress, 516 cyclic deformation, 256 displacements behind, 366-367, 369 distribution of reactions near, 385-387 effective stress intensity factor, 465 finite-element mesh, 322-323, 365, 383 load versus COD, 375-377 opening load as function of distance from free surface. 204-205 partially closed, 26 plastic zones, maximum and minimum load, 350, 352 shielding, 361-362 strain, 44 behind, 368 opening displacement and, 52, 54 at point of Mode I opening load, 59 stress fields, 349, 352 stress state, 321, 483, 485 Crack-tip opening displacement, see CTOD Crack velocity, frequency role, 119 Crack wake, 59 closing, stress intensity factor as function of, 572-573 length and state of stress, 568-582 baseline propagation data, 571-572 experimental procedure, 569-572 low-high loading, 576-581 surface removal, 573-574 test matrix, 571 reduction by saw cutting, 570 removal, 571-573

residual stresses, 349, 352 Cryogenic temperature, 62 CTOD, 171, 279, 285 applied stress intensities, 179-181 Dugdale model approximation, 288 experimental and theoretical values, 290-291 load-crack mouth opening displacement curve, 181-182 maximum and minimum, 336 at maximum and minimum load, 355-356, 358 oxide thickness and, 63-64 plasticity induced closure, 467 threshold tests, 565 CTOD gage, 219 Elber, 262, 530, 640 location, 215-216 Cyclic deformation, crack tip, 256 Cyclic loading, 398, 437 effective load range, 441 Cyclic stress-strain curve, 56

D

Damage tolerance, 491 Decreasing load threshold test crack length versus cycles, 554-555 growth as function of stress intensity factor, 557 Deformation measurement locations, 188 reversed plastic behavior, 348 Delay behavior, high stress ratios, 532-533 Dimensional analysis, plane strain, 320-322 Direct observation, crack closure, 16 - 17Displacement profiles, behind crack tip, 369 Dugdale-Barenblatt crack model, 132 modified, 439

Dugdale-Budiansky model, 476 Dugdale model extension 288, 288 modified, 285, 459–461, 640–641 analytic method, 462–466 plastic zone size, 439 Dugdale strip-yield model, 344 Dunnett's critical *D* statistic, 245 Dunnett's statistical procedure, 233

E

Elastic analysis, finite-element analysis, 400-401 Elastic compliance technique, 133 Elastic crack surface displacements, 209-211 Elastic-plastic analysis finite-element analysis, 314, 344, 358-359, 401-402, 414, 641 finite-element model, 361–362 two dimensional, 344-345 procedure, 435 Elastic-plastic deformation, 398, 401 Elastic-plastic elements, crack surface, 461 Elastic-plastic fracture, 319 mechanics parameters, 343 Elastic-plastic stress, distribution, monotonic loading, 418-419 Elastic-plastic stress-strain, 392 Elastic singularity, 389 Elastic stress analysis, 432-435 distribution, monotonic loading, 418-419 Elber CTOD gage, 262, 530, 640 Elber's closure model, 140 Elber's concept of closure, 132 Elber's equation, 131 Electrical potential drop method, 18 Electro-discharge machined notch, 281, 620-621 Electrohydraulic fatigue machine, 217, 219

Electro-servo-hydraulic testing machines, 306 Elliptical cracks, 583 Extended body force method, 477

F

Far-field compliance methods, 638 Far-field crack closure, 193–195 measurements, 87 versus near-tip crack closure, 104-108 FAST-2, 56, 58, 132 comparison with measurements, 58 Fatigue damage, interaction effects, Fe-binary alloys, 112 Finite-element analysis, 300, 319, 342, 398-413 aluminum alloy 2124, 305, 309 constant-amplitude loading, 403-409 single-spike overload, 409–411 crack growth and closure analysis, 402crack opening load, 335 elastic analysis, 400-401 elastic-plastic, 314, 344, 358-359, 401-402, 414, 641 equilibrium equations, 401-402 idealization of specimen, 401-402 incorporating eight-noded hexahedron element, 399-400 middle-crack tension specimen, 400 plane strain, 322-324 specimen modeling, 402-403 two-dimensional, 399, 417 Finite-element discretization, 303, 308 Finite-element model, 361–362 plasticity-induced closure, 375 two dimensional, 344-345 Finite-thickness plates, crack-closure behavior, 399

Fleck's method, 60-61 Flexibility method, 432-435 Flight simulation loading, 491, 642 Flow stress, 285, 287 Forman's equation, correlation based on, 523-525 Four-point bend specimen, 198 Fractography checking prediction techniques, 28 - 29variable amplitude loading, 100–101, 105 Fracture mechanics, 149, 361–362, 414, 548, 598 application, 139 see also Linear elastic fracture mechanics Fracture mode, in vacuum, 563 Fracture surface, 66, 68 asperity contacts, 179, 181, 542-543 β -annealed, 99, 102 contact during crack closure, 14 crack in sheet material, 12 mismatch, 39, 536 overload crack front, 533 oxide on, 565 partial contact, 536 polycrystalline specimens, 115 sheet material, 12 single-crystal, 114-115, 117 Frequency effects, 112

G

Gage length, 463
Gaseous environment, 88–89

near-threshold crack growth behavior, 78–80

Gauss-Siedel iterative technique, 363–364
Geometric asperities, 112, 116
Governing equations, plastic flow, 439–440
Grain boundary closure, 36, 41–42
Grain size, 62, 88

binary Fe-Si alloys, 115 near-threshold crack growth rates effects, 70–71 Growing fatigue crack active plastic zones, 337–339 comparison with stationary and tearing cracks, 333–334, 336–337 plastic zone distribution, 337–339

H

Hertzberg's hypothesis, 575-577 HEXNAS, 399 High strain fatigue, 279-299 block history and corresponding hysteresis loop, 282 closure behavior during variable amplitude cycling, 291-296 comparison of loading histories, 296-297 correlation of constant amplitude crack growth, 285-291 crack-opening, stresses as function of stress level, 284 crack propagation, 297 electro-discharge machined notch, 281 experimental program, 280-284 opening and closing levels, 284-285 specimen geometry, 281 HiLo crack propagation tests, 392-396 numerical simulation, 395-396 History of knowledge development, 5 - 7

I

IMI 550
 β-annealed microstructure, 95–96
 constant amplitude crack propagation rates, 98–99
 mechanical properties, 95
 IN9021-T4, experimental and predicted growth rates, 36–37

Inconel 706 crack closure, 80, 82 temperature and R ratio effects, 79-81 Incremental polynomial smoothing routine, modified, 612 Interface transmissivity, 539, 541 Interferometric displacement gage, 186, 195, 621 principle of operation, 153 procedure, 187 schematic, 188 Interferometric strain/displacement gage, 271-272, 640 Irwin plane stress plastic zone size, 367 J integral, 279, 285 correlation of constant amplitude crack growth, 286, 288

K

Kinematic hardening model, 348

L

Landing gear loading, 452-455 Laplace operator, 313 Large cracks closure as function of crack length, 622-624 load as function of crack length, 622 - 623versus maximum stress intensity factor, 624 crack growth rate, 156-159 as function of effective stress intensity factor, 85-86, 631-632 surface flaw, 625-627 load-CMOD plot, 621-622 specimen geometry, 620 testing procedure, 621 Life prediction, 304, 414, 437, 491 Linear elastic fracture mechanics, 279, 302, 548-549, 617

658 MECHANICS OF FATIGUE CRACK CLOSURE

Linear elastic fracture mechanics-Continued elastic stress fields, compared with crack closure ligament model, 419 stress intensity factor, 371 Load-cancelled displacement traces, 142-143 Load-crack opening curves, residual stress determination, 55-56 Load displacement, 172, 214 Load history, 186-187, 639 block, 282, 291-292 high strain fatigue, 296-297 load-shedding tests, 506-507 techniques, 187-189 in terms of maximum stress intensity factor, 189 test matrix, 189-190 Loading, 62, 89, 121-138 comparison with literature results, 128-132 crack closure dependence, 124-126 crack propagation, 141 effects of artificial levels of closure, 142 experimental techniques, 122-124 flight simulation, 491, 642 local and remote closure measurements, 125-128 low-high, 576-581 monotonic, elastic and elasticplastic stress distributions, 418-419 rates, 140-141 based on closure levels, 142 - 144decreasing crack closure levels, 145 stress intensity factor, increasing and decreasing procedures, 144-145 see also specific types of loading Load interactions, 568

Load ratio, 62 Load shedding, 30 2024-T3 aluminum alloy, 507-508 stress intensity factor, 552-553 Load spectrum, shapes, 27-28 6% load-step tests, 2024-T3 aluminum alloy, 509-513 constant-maximum stress intensity factor tests, 512-513 growth rate against stress intensity factor, 509-511 opening load, 510-511 threshold and effective threshold stress intensity factor, 511-512 18 and 30% load-step tests, 2024-T3 aluminum alloy, 513-514 Long cracks crack propagation, 304, 307-308 growth rate, 302-303 Low-cycle fatigue, 279, 548

M

Macrocrack, 29-30 crack closure, 10-11 difference from microcracks, 9 growth, 30 structurally sensitive growth, 14-16 Measurement, 157-158, 160, 171-185, 197-214, 219-220, 587, 639-641 experimental procedure, 173-175, 198-199 interferometry measurements, 202-205 load-displacement data, 175-176 numerical analysis, 175, 209-210 significance, 140 standardizing, 222-229 see also CMOD; CTOD Mechanical parameters, 583

Mechanisms, 5, 63–64, 87, 121, 172, 301, 304-305, 461, 583, 586, 637-639 constant amplitude cycling, 98-102 crack closure, 8-16 experimental procedures, 95-99 far-field versus near-tip closure, 104-108 materials and experimental procedures, 113-114 microstructural effects, 108 model, 115 residual stress and closure concepts, 95 retardation following tensile overload, 94 transient growth rate response, 109 variable amplitude loading, 98-103 Mesh System I, II, and III, 382 Metals, 171 Microcracks, 29, 149, 617 crack closure, 9-10 difference from macrocracks, 9 Microscopical observations, 6 Microstructure, 5, 62, 65, 88 α/β -processed, 173 dual phase steel, 73 effects following tensile overloads, 107-108 threshold values, 311 Middle-crack tension specimen, 400 finite-element idealization, 401-402 modeling, 402-403 Minicomputers, 149 Mode conversion, 536 Models, 44, 56-57, 293, 477 asperities, 461 closure mechanisms, 115 crack closure, 44, 56-57, 477 crack growth, 437, 441-443 crack opening, 437

Dugdale-Barenblatt, 132 Newman's, 132 see also specific models Monotonic loading, elastic and elastic-plastic stress distributions, 418-419

Ν

Near-tip closure, 262 versus crack length, 192-193 versus far-field crack closure, 104-108 local. 265 plane stress, 265 Near-tip crack, profile evolution, 385-386 Newman's crack closure model, 132-134 comparison with experimental results, 133-134 Newman's model, 285 Newman's prediction, 275-277 Newman's simulation model, 59 Newton interferometer, 600-601 Nickel base superalloy, see René 95 3-Ni steel, chemical composition, 231 crack growth rate, 242 mechanical properties, 232 No-growth threshold force, 393, 396 Nondestructive evaluation, 536 Nonpropagating crack, 365, 475 hysteresis curves, 484-486 Notch plastic zones, 350-351, 353 stress fields, 350-351, 353 Notch tip, effect of asperities near initial, 468-470 Numerical analysis, 175, 209–210 aluminum alloy 2124, 306, 308 Numerical simulation crack growth threshold, 381-383

Numerical simulation—Continued Hi-Lo crack propagation tests, 395–396

0

Offset axis method, 206 O-order fringe, 199 Opening force mesh independent determination, 390-392 numerical definition, 384 variation versus mesh length, 387-388 Optical interferometry, 270 fringe patterns, 201-202 O-order, 199 PMMA, 602 PMMA, 202–205, 643 polymers, 197 procedure, 198-199 surface under near zero load, 604-605 Overload aluminum alloys, 592–595 closing level, 296-297 effects, 583 growth delays, 642 high stress ratio, 528 retardation, 20-21, 596 plasticity-induced closure effects, 37-38 prediction, 593, 595 residual stress, 106 stress range ratio variation, 592-593 strip yield model effects, 446–448 tunneling following, 534 Oxidation, 548 Oxide buildup, 562 thickness and crack-tip opening displacement, 63-64 formation, calculation of volume change of base metal during, 566

Oxide-induced closure, 63, 66–69, 77, 112, 549, 562, 638 Oxide thickness determination, 551–552 temperature effects, 76

P

Paris crack growth regime, 23 Paris law, 139–140, 516, 612 modified, 418 Paris' relation, 472 Paris type equation, 577 Partially closed crack, 216 Phase transformation, 62 Plane strain, 11-12, 290, 319-342, 568 crack growth simulation, 328, 330 crack opening behavior, 330-337 dimensional analysis, 320-322 finite element analysis, 322-324 opening levels, 297 plasticity-induced crack closure, 340 plastic zone distribution, 337–339 stationary crack, 324-327 strain hardening, 354, 356 tearing crack, 327-329 transition to plane stress, 24 Plane stress, 11-12, 290, 342, 568 analysis, 363 closure, 36 crack growth analysis, steady state, 132 crack opening, 357-358 opening levels, 297 plastic tip zone, 30 plastic zone sizes, 572-573 region Po, 587 transition from plane strain, 24 Plastic deformation, 380, 437–438 Dugdale hypothesis, 477 Plastic flow, governing equations, 439-440 Plasticity, 62

Plasticity-induced closure, 44-61, 262, 314, 319, 335, 343, 438, 549, 562, 637-639 analysis, 464 approach, 362-366 closing and maximum stress intensity factor, 624 compressive loading, 82-84 crack opening, 462 displacements, 48-51 crack size, 84-86 crack-tip strain, opening displacement and, 52, 54 displacements behind crack tip, 366-367 dual phase steel, 70-74 experimental procedure, 45 finite-element mesh, 364-365 finite-element modeling, 375 future research, 86-88 gaseous environment, 78-80 loading condition, 79-84 load versus CMOD, 374-377 models, 87-88 opening and closing stress intensity factor, 371-373 opening load magnitude, 47-48 plane strain, 340 plastic wake formation, 369 relative strength, 466-468 residual displacements, 52-53, 55 retardation effect of overload, 37–38 significance, 36 strains, 51-52 stress ratio effects, 36, 79-82 surface displacements, 573 temperature effects, 74-77 transition from roughness induced closure, 574-576, 643 Plasticity induced crack opening, 438 Plasticity model, 346 Plastic singularity, 389 Plastic strain singularity, 392

Plastic strain tensor, variation, 390-393 Plastic tip zone, plane stress, 30 Plastic wake, 319-320, 342, 366, 643 decays, 320 fields, 24 formation, 369, 399 Plastic zone, 437 active, 338-340 distribution growing fatigue crack, 337-339 at stationary crack tip, 324, 326 Dugdale solution, 444 maximum and reversed, 350, 352 morphology, 312 reversed, 324, 326 secondary, 328, 337, 339 shapes numerical predictions, 313-314 plane strain, elastic-plastic, finite-element predictions, 312, 314 Plastic zone size, 11–12, 290, 300 center-cracked panel, 324, 326 correction, 372 cyclic, 291 Dugdale, 439 Irwin plane stress, 367 near-tip plane stress, 265 plane stress, 572-573 relationship, 39 secondary and primary ratio, 444 small-scale yielding, 320 tearing crack, 327, 329 T-stress, 321 PMMA, 197, 639 backface strain, 206-207 CMOD measurements, 206-207 crack length versus elapsed cycles response, 200 crack opening profile, 203-204 cyclic loads, 198 elastic modulus, 199 interference fringe patterns, 201-202

PMMA—Continued load-displacement record, 205-206 mid-plane crack surface displacements, 210, 212 optical interferometry, 202-205, 643 surface flaws, 598-616 absolute values of closure load measurements, 610-611 closure/opening load definitions, 605-607 COD measurements, 601-602 COD profile, 602-605 crack growth, characteristics, 614-615 effective stress intensity factor, 611 experimental approach, 599-602 modified incremental polynomial smoothing routine, 612 stress intensity factor, 607-610 surface crack, 600-601 Type II crack, 603 threshold stress intensity factor, 601 yield strength, 199 Polycarbonate, crack unzipping behavior, 216 Polycrystalline specimens, 115, 119 Polymer, 197 Precracking, 621 Pressure vessel steel, temperature effects on crack growth rates, 74 Propagating crack, 365 Pure bending, 260-269 experimental procedure, 261-262

R

Rain-flow effect, 493–495 Rain-flow method, 642 Raju-Newman K equations, 643 René 95, 548–567 chemical composition, 550

closure measurements, 189 experimental approach, 550-552 mechanical properties, 550 oxide formation, 566 Residual displacements, 52-53, 55 Residual strain, 106 Residual stress, 44 across interface, 542-543 along crack flank, 55-57 computation, 59 determination from load-crack opening curves, 55–56 field asperity contact, 537-538 redistribution, 419-421 Fleck's method, 60-61 following overload, 106 Glinka's crack growth data, 423-425 Liu's crack growth data, 425-429 Residual stretch, distribution, 462, 465-466 Resistance, fatigue crack growth, 5 Retirement for Cause methodology, 548 Reverse slip, 112 Roughness-induced closure, 35, 39-40, 62-64, 549, 562 crack wake effects, 569 dual phase steel, 72, 74 stress ratio effects, 79-81 transition to plasticity induced closure, 574-576, 643

S

Secant modulus, 288
Sehitoglu's model, 293
Semi-infinite crack, small scale yielding, 319
Servohydraulic testing machine, 252–253
Shear lips, 12–14 environmental effects, 13
Short cracks, 149, 270–278, 300, 617, 641 closure, specimen geometry, 192

crack compliances, 274-275

- COD, measurement procedures, 272–274
- growth rate, 361
- load-COD plots, 274
- load-displacement plot, 273
- opening load ratios, 274–275
- plasticity induced closure, 361
- through-thickness, 314
- Single crystal, 112
 - average and maximum step height versus frequency, 115, 118
 - crack opening stress intensity, 115, 117
 - fracture surface, 114-115, 117
 - geometric asperities, 116
- Single-spike overload, constant-amplitude loading, 409-411
- Slope deviation technique, 175
- Small-crack effect, 149, 165, 362, 617
- Small-crack specimen, 152
- Small cracks, 6, 62, 149, 270, 617-635, 644
 - crack-closure levels, 621-624
 - crack driving force, 303
 - differences between types, 10
 - growth behavior and crack closure, 84-85
 - growth rate, 149, 156–159, 302–303, 625–633
 - as function of effective stress intensity factor, 85-86, 631-632
 - material condition effects, 164 surface flaw, 626–627
 - high strain, see High strain fatigue length, dependence of closure,
 - stress intensity factor, 157-158, 160 material, 618-619 test conditions, 620 testing, 151, 154-155
- Small-scale yielding, 279, 285, 342–360, 439 analysis, 344–346
 - background, 343

constitutive model, 343-344 crack growth, 319-320 current needs, 343-344 current work, 344 notch plastic zones, 350-351, 353 semi-infinite crack, 319 stress history, 346-348 stress-strain response, 346 Specimen geometry, 186-187 Spring stiffness, 322, 402, 415 S-shaped unloading curve method, 475-488 crack propagation rate, 482-486 curve obtained from experiments, 483-484 effective stress range, 485-487 material, specimen and experimental procedures, 481-483 stress and strain relationship, 481, 483-484 stress state near crack tip, 483, 485 Stainless steels, 121 chemical composition, 122 compressive loading effects, 82-83 effective stress intensity range ratio, 124–125 mechanical properties, 123 Static stress, average, 543 Stationary crack active plastic zone, 340 comparison with growing fatigue cracks, 333-334, 336-337 crack opening profile, 324-325 plane strain, 324-327 plastic zone distribution at tip, 324, 326 Statistical approach, 230-246 Cochran's test for equality of variance, 244 expanded control interval combined cycles, 237-238 separate cycles, 236-237 experimental procedure, 232-233 materials, 232 opening loads, 233-234

Statistical approach, opening loads-Continued crack growth rates and, 241 uniform intervals, separate cycles, 234-236 validation, 238-241 Steel chemical composition, 280, 517 crack closure, 78, 80 environmental effects, 78 crack growth rates, 144, 146 surface, 267-268 dual phase, 62, 88 crack growth rates, 71-72 microstructural features, 73 near-threshold crack growth rate effects, 70-74 threshold stress intensity, 73 fatigue loading variables rates, 142, 144 grain size, 70 low carbon, small crack growth behavior, 84-85 mechanical properties, 280, 518 Stereoimaging, 45, 123, 133 Stiffness matrix, 364 Stiffness truss elements, 345 Strain behind crack tip, 368 parallel to loading axis, 51-52, 54 perpendicular to loading direction, 51, 53 plasticity-induced closure, 51-52 range as function of closed crack length, 51-52 Strain gage compliance measurements, 17, 20 position, 518 techniques, 516 Strain hardening, 342, 354–355 plane strain, 354, 356 Stress amplitude versus notch depth, 40 analysis, 437 crack opening, 131

fields, crack tip, 349, 352 history, small-scale yielding, 346-348 level, 342 crack opening, 345 mean, 414 nonsingular, 312–313 normal distribution, HiLo test, 394, 396 out of plane, 343 residual, 414 Stress concentration factor, 324 Stress function, 313 Stress intensity factor, 6, 536 applied, 150 versus effective, 227-228 closing as function of crack length/ width, 555-559 as function of crack wake, 571-572 as function of distance from transition, 580 as function of small crack length, 157–158, 160 as function of specimen thickness, 573 increase after reinitiation of growth, 574 increase after transition, 575-577 versus maximum, large cracks, 624 versus measurement location, 190-191 measured values, 577 plasticity induced closure, 371-373, 575 roughness induced, 575 short cracks, 192 COD_{sub} relation, 471 correlation with effective, 255 crack growth life, 427 crack in infinite plate, 456-457 crack opening, 39, 247 determination, 251-254

versus maximum statistical approach, 263-264 plane strain, 265 crack shape factor, 595 effective, 58, 465, 469, 475, 517, 545, 599 after mean load change, 258 closure loads, 629-632 constant amplitude loading, 453-454 crack tip, 607-609 as function of reciprocal stress intensity factor, 48 as function of stress ratio, 140 minimum and maximum, 424 PMMA flaws, surface flaws, 611-614 utility, 160–163 VA load history, 26 variation along crack front, 26 effective closing, crack propagation rate, 483, 485 effective opening, crack propagation rate, 482, 485 effective threshold, 505 variation with stress ratio, 510-514 equations, 515, 643 as function of crack length, load shedding rates, 552 as function of stress ratio, 22-23 global, 545 linear elastic fracture mechanics, 371 loading conditions, 271-272 load shedding, 551, 553 local, acoustic waves, 543-546 maximum, 131 crack propagation rate, 482, 484 relation with stress intensity range ratio, 127, 475-476 unloading from, 325 measured and predicted, 51 modified form, 140 nomenclature, 248

opening, 459 comparison of CMOD and backface strain, 179 crack length effect, 175, 177 - 178dependence on numerical procedure, 178, 183 plasticity induced closure, 371-373 variation with maximum, 378 Paris law, 418 plastic wake, 643 plate of finite width, 519 PMMA flaws, surface flaws, 607-610 residual stress, 55 specimens, 271 surface-layer removal, 643 threshold, 6, 248-251, 302 dual phase steel, 73 effects of yield strength and stress ratio, 66-67 environmental effects, 78-79 load-shedding rate and, 505 PMMA, 601 temperature effects, 75-77 variation with stress ratio, 510-514 variation, aluminum alloy 2124, 311, 314 Stress intensity range ratio effective, 11, 124-127, 129, 421 as function of crack length, 293 Glinka's crack growth data, 423-425 and maximum stress intensity factor, 475-476 relation with maximum stress intensity factor, 485-487 versus stress ratio, 421-424 influence of extent of closed crack, 128-129 literature results, 128-132 relation to stress ratio, 520-522 variation from overloads, 592-593

Stress ratio, 15, 260, 342, 505, 516, 583 aluminum alloys effect, 588-590 compliance before and after overload, 531 constant amplitude growth, 297 crack initiation near center, 534 crack opening stress effects, 421-423 crack tunneling, 534 delay behavior, 532-533 effective, 424 experimental methods, 529-530 high, 528–535 load versus CTOD, 530-531 materials, 529 near-threshold crack propagation rates, 79-82 plasticity-induced closure effects, 36 propagation rate effect, 517 relation to stress range ratio, 520-522 roughness-induced closure, 39 SEM examination, 533-534 stress intensity factors as function of, 22-23, 66-67 threshold behavior, 254-255 Stress spectra, 491 Stress state effects, 583 aluminum alloys, 590-592 crack growth rates, 591 near crack tip, 483, 485 see also Crack wake, length and state of stress Stress-strain relations, loading and unloading, 479 Stress tensor, 319-320 Striation counting technique, 577 Striations, fracture surfaces, 18-19 Strip yield model, 437-458, 641 basic equations, 456 comparison with CORPUS, 450-452 constant amplitude loading, 444-445

crack growth law, 441 crack opening load, 445 crack surface, displacements, 456-457 discretization of problem, 442-444 elastic problems, 438–439 landing gear loading, 452-455 mathematical model, 438-442 crack growth model, 441-443 crack opening load, 441 plastic flow governing equations, 439-444 opening load, 453 single overloads and underloads, 446-448 stress intensity factor, 456 variable amplitude loading, 448-452 Structural steel, 516 Surface crack crack growth rate, 590 fully closed, 643-644 plasticity-induced closure, 262 specimen, 600 under pure bending, see Pure bending void formation, 601 see also Small cracks Surface-flaw crack growth rate, large crack, 625 see also Crack growth rate, surface flaw; PMMA, surface flaws Surface-layer removal, 643 Surface roughness environment and, 13 temperature effects, 76

T

Tearing crack, 321 comparison with growing fatigue cracks, 333–334, 336–337 plane strain, 327–329 Technical significance, crack closure, 7-8 Temperature, 88 elevated, 548 threshold tests, 553, 562 near-threshold crack propagation rates, 74-77 Tensile overload, 93 crack growth effects, 96-97, 102, 105 - 106parameters associated with, 97 post-overload retardation variation, 107-108 retardation following, 94 Tension plastic zone, 256 Thickness effects, 25, 36 Three-dimensional analysis, 398 Threshold behavior, 247-259 in air and in vacuum, 250 crack opening, statistical approach, behavior, 251 general form, 248-249 method to check, 251 Threshold test, 193, 551, 643 closing stress intensity factor as function of crack length/width, 555-559 CTOD, 565 elevated temperature crack arrest, 562 crack length versus cycles, 553 see also Decreasing load threshold test Through-thickness cracks, 277 Titanium alloys, 93, 171, 247 Bodner coefficients, 363 chemical composition, 619 crack opening stress, 131 crack tip area, 174-175 mechanical properties, 174 microstructures, 173 small cracks, see Small cracks see also IMI 550 Titanium-aluminum alloys, 149-167 α -phase, 150 asperity-induced crack closure, 164

chemical composition, 151, 252 crack closure levels, 158, 160 measurements, 157-158, 160 crack growth rate, 156-159 effective stress intensity factor, utility, 160-163 experimental methods, 151-154 heat treatment, 152 load versus crack mouth opening displacement, 154-155 materials, 150-151 mechanical properties, 253 small-crack effect, 149, 165 small-crack testing, 151, 154-155 tensile properties, 152 Vickers hardness indentations, 153 Transformation closure, 35 Transient crack growth rate behavior, 93 Transitional closure, 35-36, 40-42 Transmission coefficient, aluminum alloy, 539 Triangular constant strain mesh, 209-210 Truncation level, definition, 502 T-stress, 324, 337 Tunneling, following overload, 534 **TWIST**, 642

U

Ultrasonic techniques, 537 interaction with asperities, 538-542 Underload, strip yield model effects, 446-448 Unloading compliance, 459 Unloading elastic compliance method, 475-478 analytical method, 477-478

V

Validation, statistical approach, 238-241

Variable amplitude cycling, 279 closure behavior during, 291-296 Variable amplitude loading, 25-26, 30-31.93 CORPUS model, 449-450 crack closure, 101-103 crack opening, 448-452 fractography, 100-101, 105 growth rate data, 99-100 stationary test, 27 Vickers hardness indentations, titanium-aluminum alloys, 153 Visco II, 363-364

W

Westergaard stress function, 456 Williams' stress function, 313

Y

Yield strength, 62, 88
binary Fe-Si alloys, 115
near-threshold crack propagation rates, 65–70
stress intensity factor effects, 66–67
Yield stress
normalized, 405–406
spike overload effects, 408–410